# PATENT SPECIFICATION

DRAWINGS ATTACHED

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## COMPLETE SPECIFICATION

## Improvements relating to Electromechanical Transducers

We, ENDEVCO CORPORATION, a Corporation organised and existing under the Laws of the State of California, United States of America, of 801 South Arroyo Parkway, Pasadena, California, United States of America, do hereby declare the invention, for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement:—

This invention relates to electromechanical transducers for converting mechanical displacements into electrical signals.

Such transducers may be employed for measuring acceleration, velocity, pressure, or simply the relative displacement of two mechanical parts or the strain in a single mechanical part. In each case a transducing element is utilized for detecting the relative displacement of two parts or areas and for developing the corresponding electric signal. Such relative displacement has heretofore been measured with various kinds of strain gauges, some of which are of considerable weight, some of which are bulky, some of which are not very sensitive, and some of which are very expensive. Some of the strain gauge elements that have heretofore been employed as parts of transducers have been of the resistance type. Such strain gauge elements change electrical resistance when subjected to strain. Commonly, a resistance strain gauge is made of metal wire such as platinum, or nichrome, or constantan, in which the change in resistance is due almost entirely to the change in length and cross-sectional area while maintaining a constant specific electrical resistivity. Others have employed piezoresistive materials, generally a semiconductor such as silicon doped with boron, in which the effective resistivity changes when the material is subjected to strain. A much larger change in resistance is experienced with piezoresistive materials. (By resistivity is meant resistance-per-unit-length for an element of unit cross section).

According to the present invention an electromechanical transducer includes a pair of substantially rigid members connected to one another by means permitting relative hinging movement between them, and at least one piezoresistive semiconductor strain gauge element having end portions secured respectively to the two rigid members and an intermediate portion extending across the gap between them, and spaced from the axis of hinging so as to be subjected to extension or compression by the hinging movement.

Conveniently the means permitting hinging movement between the rigid members comprise a Cardan hinge, that is to say a hinge arranged to permit hinging movement by bending of the material of the hinge. Such a hinge may be constituted by a web formed integrally with the rigid members but of reduced section so as to permit the bending. For example the rigid members and hinge may be in the form of an elongated beam having a web of reduced section to constitute the hinge. Thus in one arrangement the beam has in one face a groove extending transversely to its length leaving a reduced web to form the hinge spaced from the plane of the said face, and the strain gauge element bridges the groove so as to be spaced from the hinge axis.

As claimed in the present applicants' British patent specification No. 18324 of 1965 (Serial No 1111133.) (from which the present specification is divided out) the element may comprise a pair of pads connected by a neck having a cross-section substantially smaller that that of the pads and formed integrally with them. The material may comprise a

semiconductor such as germanium, silicon, carbide or gallium arsenide, which may be doped. A preferred material is predominantly silicon doped with a small proportion of boron. Such a material may have a resistivity of the order of 3 ohm centimetres.

Preferably the neck portion is of such dimensions as to form a non-buckling or Euler column. By shaping the neck and proportioning the dimensions of the neck to render the element non-buckling it may be employed to measure compressive forces as well as tension forces without subjecting the element to a pre-tension or bias force. It will be apparent, however, that many of the advantages of the invention can still be attained if the element is not non-buckling, and is only used in tension.

Further features and details of the invention will be apparent from the following description of certain specific embodiments, given by way of example, with reference to the accompanying drawings in which:—

Figure 1 is a perspective view of an element for use in a transducer according to the invention,

Figure 2 is a plan view of the element,

Figure 3 is an elevation of a simple accelerometer embodying the invention,

Figure 4 is a wiring diagram of a bridge circuit employed for detecting changes in resistance of the element,

Figure 5 is a wiring diagramm of a bridge circuit employed for detecting differential changes in resistance of two elements.

Figure 6 is a perspective view of part of another simple accelerometer and

Figure 7 is a wiring diagram of another bridge circuit employed for detecting differential changes in resistance of two pairs of elements.

In Figures 1 and 2, the strain gauge element 8 is in the form of a very small elongated rod or block of rectangular cross-section of semi-conductive material, having a reduced neck 10 of smooth hour-glass configuration separating two enlarged pads 12 and having a pair of electrical leads 14 conductively bonded to the pads. The element has an overall length $L$ of 0.25 cm, overall width $W$ of 0.13 cm, and a thickness $H$ of 0.028 cm. The pads are of square shape as viewed from the top, being about 0.13 cm on each side. The reduced neck is formed by means of a pair of opposed notches 16 formed in opposite sides and by a second pair of notches 18 formed in the other sides. The notches 16 have semi-cylindrical surfaces at their inner ends. The radii of these surfaces are about 0.03 cm. The notches 18 are cut to a depth of about 0.007 cm. As a result, the reduced neck has a cross-section of about 0.015 cm $\times$0.015 cm, the smallest section having an area of about 0.0002 cm$^2$. The neck is very nearly of square cross-section, but is slightly rounded at the edges by chemical etching. The neck is joined by outwardly flaring portions that connect the neck to the pads by means of smooth curves.

In effect, the portion of the strain gauge element that lies between the pads is an Euler column of stubby smooth waisted or hour-glass configuration that is free of any lateral support. The length $a$ of the neck, that is the distance between the pads, is somewhat greater than the minimum thickness of the neck, that is the thickness at its narrowest portion. In any event, the length of the neck is less than that length (about three or four times the minimum thickness of the neck) which could result in buckling. The entire element is in the form of an Euler column, though this is not always essential to the operation. In other words, in the element illustrated, if longitudinal compressive forces are applied along the longitudinal axis X—X of the element, the element would not bend or buckle but would gradually enlarge or thicken at the neck until crushed. While buckling could occur if the element were of great length so that, in effect the complete element would be an elongated rod or bar, still the neck portion of the element between the pads could be considered as having the properties of an Euler column when viewed in terms of forces applied to the element at the portions of the pads nearest the neck.

The strain gauge element is symmetrical about its central axis X—X, being symmetrical about two mutually perpendicular planes that pass through that axis. With this arrangement, the neck is coaxial with the central axis and lies midway between the lateral edges and surfaces of the pads.

The importance of employing a reduced neck that is non-buckling lies in the fact that the strain gauge element may be compressed up to the crushing point without buckling. This facilitates measurement of compressive strains as well as tensile strains over a large range of strain without biasing the unit with a static tension force. This, in effect, doubles the range of strain which can be measured.

Figure 3 shows a simple type of accelerometer in which a mass $M$ is fastened to one end of a flexible arm 44, the other end of which is firmly attached to an object 46 undergoing oscillatory or other acceleration along an axis Z—Z perpendicular to the length of the bar 44. In this case, assuming that the axis Z—Z is vertical and the bar 44 has a flat upper surface, one strain gauge element 8 is fastened to the bar 44 on opposite sides of a groove 48 cut in the upper surface of the bar, and another is fastened on opposite sides of a second groove 49 cut in the lower surface of the bar. The grooves establish a Cardan hinge at which the bending of the bar is greatest, thus increasing the sensivity of the unit.

In this particular accelerometer, the upper element is extended when the lower element is compressed and vice versa. Thus, the resistance of one of the elements increases when the resistance of the other decreases.

There are, of course, numerous known ways in which the changes in resistance of the element may be measured or otherwise utilized, In all cases, care is exercised to insulate the pads 12 from each other except through the neck 10 in order to avoid shortening or shunting the neck through an external circuit. Such insulation may be established most easily by bonding the elements to the objects to which they are attached with insulating cement.

For illustrative purposes, a bridge circuit that may be employed to record the changes in strain is illustrated in Figure 4. There it will be noted that the element 8 and resistances R1, R2 and R3 are connected in the four arms of the bridge. A DC signal from a source *S* is supplied to one diagonal of the bridge and a recording system RS, such as a conventional amplifying system and recording oscillograph, is connected to the other diagonal of the bridge circuit. In this case, the bridge circuit may be unbalanced by manipulation of the values of the resistors such as by adjustment of the variable resistor R1. The bridge is so unbalanced that the polarity of the signal that is fed to the recording system always remains the same throughout the range of strains to be detected, regardless of the value of the resistance of the element 8.

The bridge circuit of Figure 5 may be employed to detect changes in the differences in resistance between the two elements of the accelerometer of Figure 3 during measurement of acceleration. In this case also, the bridge is unbalanced so that the polarity of the signal that is fed to the recording system remains the same regardless of the sign of the acceleration.

In another form of accelerometer, illustrated in Figure 6, one pair of elements 8*a* and 8*b* are employed on the upper side of the arm 44 and another pair of strain gauges 8*c* and 8*d* are employed on the lower side. In such a case, the effects of the strains produced may be added by connecting the gauges of each pair in opposite arms of a four arm bridge as indicated in Figure 7.

Various piezoresistive materials may be employed in the element 8. The most satisfactory materials are semiconductor materials, such as silicon that has been doped with a small proportion of boron. Other suitable materials include suitably doped germanium, doped silicon carbide, and doped gallium arsenide. A material having a resistivity of 3 ohm-cm at room temperature while the material is not subject to strain has provide to be very satisfactory. With such a material, the strain gauge element having the dimensions described above has a resistance of about 350 ohms. This value of resistance makes the strain sensitive element very satisfactory for use in a strain gauge for many reasons which are well known. For one thing, the resistance is sufficiently low to avoid excessive pickup of stray signals induced from power lines and the like, but is sufficiently large to facilitate matching with other resistors in a bridge circuit or otherwise matching impedances of an amplifying system, whether they be of the solid-state type or of another type. Generally, a resistance between 10 ohms and 3000 ohms is most satisfactory.

This invention makes possible the construction of strain gauges which have high gauge factors and still do not exhibit extreme changes in characteristics with temperature in spite of the fact that the strain-sensitive part thereof is not intimately bonded to the object undergoing test. To appreciate the advantage of the invention in this regard, it should be borne in mind that the gauge factor is a property of the material employed and is equal to the percentage change in resistance produced by a 1% change in the strain of a rod of the material that is of uniform cross-section. As is well known, the gauge factor is high for semiconductive materials with low doping and decreases as the doping is increased. However, the temperature co-efficient of resistivity also decreases as the doping is increased.

In prior strain gauges of wire shape and composed of piezoresistive material, high gauge factors of over 150 can be attained by virtue of the fact that such strain gauges can be bonded throughout their length to the object under test so that such strain gauges readily dissipate their heat. In this invention, such high gauge factors are also attainable by virtue of the thermal properties of the neck in relation to the enlarged pads, even though the strain sensitive portion is not bonded to the object under test. The heat generated in the neck is readily conducted through the pads to the object under test. For this reason, temperatures throughout the strain gauge element are maintained nearly uniform even under conditions where heat generation varies. Thus, with this invention, high gauge factor is obtained by the use of semi-conductive material of low doping in spite of the fact that the strain sensitive element is not intimately bonded to the object under test as is the case with wire shape strain gauges. At the same time, the strain gauges of this invention are free of the difficulty of bonding metal leads to the small ends of the strain gauge of the wire shape that are composed of semiconductive material.

The maximum positive strain, or elongation, that can be detected depends upon the yield strength of the material, that is, the yield point of the strain gauge element when stretched. The maximum negative strain, or compres-

sion, that can be detected depends upon the maximum load which can be withstood by the strain gauge element without crushing. Measurements of this resistance change are facilitated by the fact that large currents can be carried through the neck of the strain gauge element without overheating. In practice, it is found that changes in resistance of ±20% occur over the range of strain which can be measured without damage to the strain sensitive element.

The sensitivity of a piezoresistive strain gauge depends upon the direction in which the strain is applied, relative to the crystal structure. In the case of silicon, maximum sensitivity is obtained in the (111) direction. For this reason, the strain gauge element is made with the axis X—X along the (111) direction of the crystal. For best results the strain sensitive element is formed of a single crystal.

By employing a piezoresistive element of the type described herein in which a reduced neck portion interconnects a pair of pads which are adapted for fastening to a pair of relatively displaceable elements and also are adapted for connection to an electrical circuit, an electromechanical transducer can be provided which has a small volume and low weight and high sensitivity and which, under some circumstances, has an exceptionally high degree of linearity for both compressive strains and tension strains over a wide range.

Thus the main advantages of the elements may be summarized as follows:—

1. The strain gauge elements make it possible to obtain a very high output for a given displacement.
2. The employment of large pads, together with a reduced neck, makes it possible to dissipate heat rapidly away from reduced portion, thus making it possible to dissipate heat away from the reduced neck without bonding the neck itself to the object being tested.
3. The element is of low weight and small volume.
4. By constructing the element as an Euler column, the element has a high stiffness, thus making it suitable for use in accelerometers or other devices which are designed to measure oscillatory movements up to high frequences.
5. At least when employed by attachment of its lateral faces to a pair of relatively movable segments that cause the element to bend, the element exhibits a high degree of linearity.
6. By constructing the strain gauge element as an Euler column it can be employed to detect compressive strains as well as tensile strains without the application of a prestressing force such as is required with wire strain gauges.
7. The strain gauge element is capable of being used to detect and measure high strains.

It will of course, be understood that the invention is not limited to the exact constructins described herein, but that the element may be embodied in many other forms and may be composed of other materials and may be incorporated in electromechanical transducers in other ways, all within the scope of the appended claims.

WHAT WE CLAIM IS:—

1. An electro-mechanical transducer including a pair of substantially rigid members connected to one another by means permitting relative hinging movement between them, and at least one piezo-resistive semiconductor strain gauge element having end portions secured respectively to the two rigid members and an intermediate portion extending across the gap between them, and spaced from the axis of hinging so as to be subjected to extension or compression by the hinging movement.

2. A transducer as claimed in Claim 1, in which the means permitting hinging movement between the rigid members comprise a Carden hinge, that is to say a hinge arranged to permit hinging movement by bending of the material of the hinge.

3. A transducer as claimed in Claim 2 in which the hinge is constituted by a web formed integrally with the rigid members but of reduced section so as to permit the bending.

4. A transducer as claimed in Claim 3 in which the rigid members and hinge are in the form of an elongated beam having a web of reduced section to constitute the hinge.

5. A transducer as claimed in Claim 4 in which the beam has in one face a groove extending transversely to its length leaving a reduced web to form the hinge spaced from the plane of the said face, and the strain gauge element bridges the groove so as to be spaced from the hinge axis.

6. A transducer as claimed in any one of the preceding claims in which the strain gauge element is of semi-conductor material.

7. A transducer as claimed in any one of the preceding claims in which the strain gauge element is of such dimensions as to form a non-buckling or Euler column.

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Agents for the Applicants

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1111134 COMPLETE SPECIFICATION

1 SHEET *This drawing is a reproduction of the Original on a reduced scale*

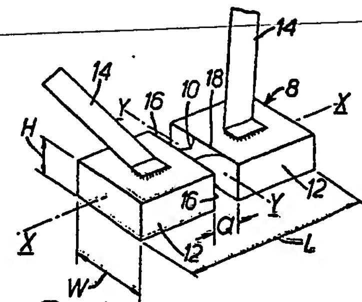


FIG. 1.

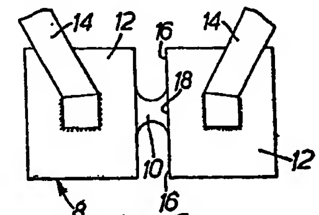


FIG. 2.

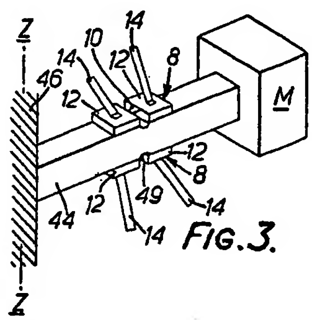


FIG. 3.

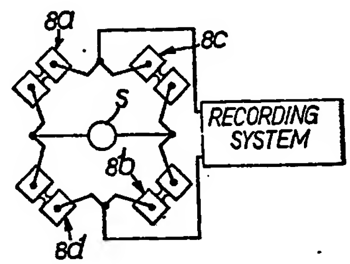


FIG. 7.

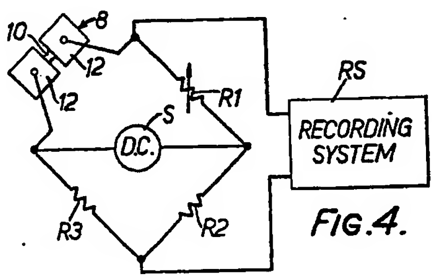


FIG. 4.

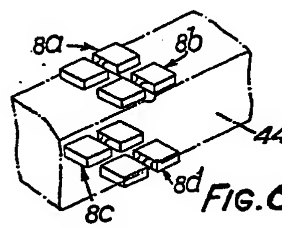


FIG. 6.

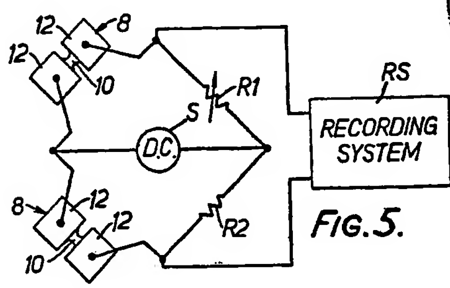


FIG. 5.